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# Decision support framework for supply chain planning with flexible demand

F. GALASSO<sup>1</sup>‡§, C. MERCÉ ‡ and B. GRABOT §

‡ LAAS-CNRS, Université de Toulouse, INSAT  
7, Avenue du Colonel Roche, 31077 Toulouse, France  
§ Laboratoire Génie de Production – ENI de Tarbes  
47, avenue d'Azereix BP 1629 65016 Tarbes CEDEX

**Abstract:** The most challenging issue of today's production management is certainly to manage networked organisations under an uncertain demand so that to provide a good service to the customer at low cost. In this article, a model of the decision making parameters involved in this management process is suggested, on the base of case studies. A mixed integer linear planning model embedded in a framework simulating a rolling horizon planning process is described on the base of this analysis. The model takes into account the capabilities of reaction of the planned system and of its environment (suppliers, subcontractors and customers), as well as the corresponding costs. The suggested simulation framework may assist the decision maker for coping with an uncertain or flexible demand, using various planning strategies. Some possible applications of this simulation framework are given in order to illustrate how it can help to solve various types of practical planning problems.

**Keywords:** Supply chain; Production planning; Decision making; Optimization; Performance evaluation; Uncertainty;

## 1 Introduction

The specialisation which has resulted from the companies' focus on their core competencies has brought most of them to work in networks. Among these networks, Supply Chains, Virtual or Extended Enterprises are often distinguished. Even if a consensus can hardly be found on precise definitions, supply chains are usually considered as networks of companies working under customer-supplier agreements and focusing on the manufacturing issues, whereas virtual enterprises are composed of equal partners not only sharing their manufacturing facilities but also their marketing or design competences through collaborative organizational structures (Nayak *et al.*, 2001). The concept of extended enterprise is another view on the same problem, based on the idea that a company is composed not only of its employees, board members, and executives, but also of its business partners, suppliers, and even customers (Information builders, 2005).

<sup>1</sup> corresponding author. email: fgalasso@laas.fr

Managing these networked organisations in order to provide a good service to the customer at low cost, under an uncertain demand, is certainly the most challenging issue of today's production management. Many research studies aim at defining optimal solutions for multi-site manufacturing, while others suggest more decentralised ways of managing this problem (see for instance surveys in Capar *et al.*, 2004; Terzi *et al.*, 2004, Tan, 2001). On the industrial side, Advanced Planning Systems (APS) (Stadtler *et al.*, 2005) provide software solutions for optimizing the material flow between and inside companies.

Nevertheless, there is still an important gap between the paradigm of multi-site manufacturing and the daily reality of supply chain management. Many contacts with companies involved in various types of supply chains, but more specifically in the aeronautic industry, have shown us that this daily reality is still mainly oriented on point-to-point relationship of independent entities, using only partial information sharing. In that context, there is an important need in decision support tools allowing a loose coupling between independent manufacturing entities in a customer-supplier context.

This paper is structured as follows. In the second part is given a short state of the art on supply chain management, allowing positioning the various research approaches on the subject. This state of the art is compared in section 3 with a view on the daily reality of networked manufacturing, drawn after many contacts made with companies working at different levels of supply chains of the aeronautic domain. A set of concepts allowing an explanation of the identified industrial practices is extracted from this insight and presented in section 4. These concepts are the base of an analytical model of a point-to-point relationship between two companies in a supply chain context. This model and its dynamic use in a simulation framework are described in section 5. Section 6 shows how uncertainty can be taken into account in this framework. Some examples illustrating how this framework can be used in order to solve various types of practical problems linked to the partial coordination between companies within a supply chain are presented in section 7: namely problems linked to supplies or to internal failures detection, facilitation of the management of degrees of freedom, integration of the forecasts through simulation and evaluation, assistance for customers/suppliers relationships management.

## **2 Supply Chain Management and Networked enterprises**

It is now a widely spread idea that companies are moving from a supply chain paradigm where each partner operates independently in its own self-interest, using only locally available information, to a fully coordinated decision-making approach, in which all information and decisions are aligned to accomplish the global system objectives (Sahin, 2005). On the software market, APS (Advanced Planning Systems) are consistent with this idea, and allow companies to optimise the material flow between several distant manufacturing entities (Stadtler *et al.*, 2005). Nevertheless, the optimisation claimed by the APS requires an accurate control of all the elements of the supply chain. In practice, this global coordination leaves a poor autonomy to each entity of the supply chain, and is therefore only possible when these entities belong to the same industrial group.

In spite of this, the idea to manage the material flow all along a supply chain through centralised optimisation has motivated a number of studies in the research literature, especially in the end of the 90's (see for instance (Christopher, 1992), (Lee and Ng, 1997),

(Stock *et al.*, 1998)). Beamon (1998) presents for instance a review on supply chain modelling techniques considering the supply chain as a whole: through deterministic, stochastic, economic or simulation models, the supply chain management and planning problem is addressed by the adjustment or optimisation of decision variables regarding scheduling, lot-sizing or inventory allocation problems. A more comprehensive survey of optimisation problems in supply chains is given by Geunes and Pardalos (2003). Having a centralised view on supply chain management requires information sharing between partners. This allows for optimisation but can also be an answer to the well known bullwhip effect (Huang *et al.*, 2003). The effects of information sharing through centralised analytical models is also analysed in studies like (Cachon and Fisher, 2000) or (Thonemann, 2002), the latter addressing the problem of an uncertain demand.

On the other hand, Kok and Fransoo (2003) point out the hierarchical nature of supply chain management but also underline the importance of decentralised decision models, both for decreasing the amount of data to be processed and for preserving a local autonomy that could be set into question by the centralised model. Therefore, the problem of supply chain management is nowadays more and more often stated as finding a good balance between centralisation and cooperation. In (Chan *et al.*, 2004), a multi-criteria optimisation model based on genetic algorithm allows for instance to compare a centralised management, in which orders are sent to the first available manufacturer, to a collaborative one. A taxonomy of the levels of cooperation has been suggested by Lauras *et al.* (2003), according to the type of data and data processing facilities exchanged between enterprises. Thierry *et al.* (2006) define a cooperation policy as an instantiation of possible behaviours for each actor of the supply chain. Nevertheless, such definition of possible behaviour could be limited as a complete autonomy of the considered actor is not guaranteed. Thus, the opportunity of initiating cooperation extending the possible behaviours should be addressed, if possible quantitatively.

Fully decentralised approaches are also a topic of interest in the research community, especially using negotiation through Multi-agent systems (MAS) (see for instance (Ulmer *et al.*, 2002), (Nissen, 2001) or (Archimède *et al.*, 2003)).

An important issue is nowadays to find the ad-hoc balance between centralised and distributed approaches. The former is able to provide a global optimisation of the supply chain, but is poorly consistent with the necessity of preserving the autonomy of each company. The latter suggests solving the problem through negotiation but is hardly compatible with the constraint of global optimisation. In these latter approaches, it seems important to ensure that any collaborative process dedicated to the definition or the specification of a customer demand can be consistently integrated at a local level. Thus, the inner production planning process of an enterprise should be addressed firstly. Zhao and Xie (1998), propose the use of heuristics in order to balance the costs of the calculated plan and schedule instability, highlighting the importance of the length of the frozen part of the customer demand. Génin *et al.* (2007) provide an interesting study positioning the concept of robustness of the plans beyond the concept of stability. The authors compare three methods for tactical planning and highlight the use of a reference plan as a good compromise between costs, stability, robustness and service levels. In these two last articles, random distributions are used in order to generate the actual demand on the base of the forecasted one.

In order to position these research studies according to examples of the daily industrial reality, a set of interviews with supply chain managers has been conducted in various companies of

the south-west part of France. This work has been done within two contexts: a French project named PICHALOG<sup>2</sup>, which has mainly performed interviews in large companies, and the European INTERREG PREMI<sup>3</sup> project, more dedicated to Small and Medium Enterprises (SMEs). The main results of these studies are summarised in next section.

### **3 A pragmatic view on real supply chains**

First of all, it is important to underline that the following considerations on real practices in supply chains do not pretend to any kind of exhaustiveness. Anyway, it seems interesting to analyse the consistence between a sampling of reality (even if not fully representative) and some of the basic assumptions of the present research trends on the subject.

#### ***3.1 Type of considered supply chains***

The main limit of this study is that it has mainly been conducted in the south-west part of France, where an important number of companies work for the aeronautic industry. A specificity compared to other large supply chains (e.g. to the electronic, agro-food or automotive industry) is that the considered products have a high added value, are complex to manufacture and require long cycle times. The demand does not concern very large quantities, and is mainly subject to slow variations through time. In that context, we are close to make-to-order production, and an important part of the uncertainty on the demand of a given company of the supply chain is linked to disturbances introduced by upstream, but also downstream partners of the chain. The well known "bullwhip effect" is a good example of this.

In such supply chains, the final entity is usually a large company which designs and assembles complex products, like aircrafts. Tier 1 suppliers can be other large companies which design and manufacture complex sub-systems of the aircraft (engine, landing gear, air circulation system, actuators...). At rank 2, these companies use smaller partners (which are often Small and Medium Enterprises - SMEs), manufacturing precision parts or simple sub-systems. Since these SMEs are often specialised in precision machining, they usually sub-contract thermal or surface treatments to specialised companies of tier 3. The raw material providers (usually steel plates) are also found at rank 3. This basic structure is made more complex by the fact that a company - or type of company - can be present at different levels of the supply chain: for instance, companies of tier 0 or 1 also use sub-contractors performing thermal or surface treatments. Therefore, these SMEs are resources shared by companies of different levels, with the result of possible conflicts.

Long interviews have been performed in twelve companies (among which 3 large ones and 9 SMEs), most of them belonging to multiple supply chains, the SMEs being suppliers of the large companies. These interviews were oriented on the identification of the way information coming from the customers was processed in order to define an internal planning, then a planning for suppliers. The main problems identified in these processes were also discussed and the usual ways to cope with them were analysed.

The number of companies interviewed seems to be enough regarding the definition of concepts based on industrial practices as highlighted by Eisenhardt (1989) in the field of the

<sup>2</sup> Pilotage Intégré des CHAînes LOGistiques (Integrated Supply Chain Control), project supported by the French CNRS in 2004 (RTP 47)

<sup>3</sup> <http://www.premi.cf.ac.uk/>

organisational researches. The most interesting points arising from these interviews are described hereafter.

### ***3.2 Main results of the interviews***

*Influence of the size of the company.* A first interesting point is that a direct correlation can be noticed between the size of the company and its maturity regarding information technology and production management. The smallest SMEs (10-30 persons), belonging to ranks 2 or 3, have often been created 15-20 years ago on a niche of high technical skills related to specialised machining. The present emphasis set by their large customers on the management aspects, like strict control of the work in progress, accurate follow up and immediate reaction in case of divergence between what is planned and what is realised, are not really fully understood as important objectives, the main interest of the SMEs still focussing on product quality. A consequence is that large investments are often realised on machines, whereas the companies are more reluctant to invest money and time on production management tool.

*Centralised vs. point-to-point relationship.* A global optimisation of the supply chain would have as a consequence the control of the whole supply chain by the final assembler. Such global coordination is against the basic principle of the customer / sub-contractor relationship, i.e. the responsibility of the sub-contractor on all its upstream activity. Indeed, the sub-contractor is responsible for his own sub-contractors or suppliers, and this responsibility does not allow any interference of the final customer in their relationships. A second and more pragmatic point underlined by the supply chain managers was that anyway, such coordination would be too complex to be efficiently managed...

An exception was noticed, related to the present crisis on the steel and aluminium markets: in some cases, the final customer helps tier 2 or 3 sub-contractors for obtaining their raw materials, its size giving him an influence that a SME cannot have when negotiating with the large companies which supply raw materials or casting parts.

When correlating the two first points, it can be seen that a major problem is that tier 2 or 3 partners, which often have a loose control of their own internal flows, have a fortiori increased difficulties for keeping control on their sub-contractors.

*Information provided by the final customer.* The large companies located at the end of the supply chains are mainly working on the base of programs, with slowly increasing or decreasing quantities according to the context (we are now in an increasing context, after a difficult situation five years ago). On the base of these programs, the companies build requirement plans for each of their first tier suppliers and sub-contractors, including slacks for covering possible disturbances. The result is a delivery planning on several years (typically 2-3 years), with quantities to be delivered by month, or even by day in some cases. This delivery planning is usually actualised every month in order to take into account the slight variations of each program.

*Contractual aspects.* A delivery plan generated by a large company is usually composed of several time zones:

- a firm zone, between 15 days to 1 month, during which the orders to the sub-contractor or supplier will not be changed (except in case of major problem),

- a flexible zone (usually some months), during which the orders can be modified inside given limits (for instance  $\pm 50\%$ ),
- a free zone, only provided to the sub-contractor for information.

It is interesting to notice that the large companies have usually a good understanding of the constraints of the SMEs. In the aeronautic area, selecting and labelling a new sub-contractor is a long (nearly one year) and costly task; therefore, partnership is usually preferred to an uncontrolled pressure on existing partners. As an illustration, a company can define a firm zone for its sub-contractor which is longer than the one provided by its own customers. This means that the customer takes the risk of making storage, in order to protect his sub-contractors from brutal variations of the demand which they could hardly bear. Another illustration is that in some cases, the large company compares the quantities they asked to their subcontractors to those asked in the previous periods. In case of important increase or decrease of the expected quantities, the company tries to smooth the demand in order to avoid any destabilization of its subcontractor. In another case, the customer guarantees that any order modified in the flexible zone will be accepted within a maximum delay of three months, even if it is not anymore required.

This protection of the sub-contractor is balanced by the possibility of the customer to break a contract and choose immediately another supplier if he can find better prices... One of the large companies has a program of externalisation in countries at low cost (Asiatic area), but another was on the contrary focusing on local subcontracting. It is worth noticing that the first results of this externalisation were quality problems, which required urgent actions on parts coming from the low cost countries, these urgent reactions being very disturbing for the sub-contractors.

These features show that the situation in the visited companies was far from a direct transmission of production plans from a down stream to an up stream partner. Because of the different sizes of the companies, and as a consequence their different capacity to bear unexpected events, load smoothing and intermediate inventories are often required inside the chain, resulting in a voluntarily sub-optimal but more robust performance of the supply chain.

*Information processing in the SMEs.* Only one of the visited SMEs (the larger one, with more than 100 employees) could be considered as working in accordance with usual production management processes, namely building a middle term production plan with rough feasibility checking, building a material requirement planning, then performing a detailed load planning, dispatching the orders and performing a strict follow-up. In half of the SMEs using production management tools from the market, these tools were mainly used for collecting the orders on the base of the delivery planning of their customers or for managing the technical data (bills of materials and routings). For different reasons, the orders were then always extracted from the production management tools and were processed using specific developments on Excel® or Access®. As a consequence, the load/capacity checking facilities of the production management tools were never used, nor their follow-up modules. Therefore, the short term management of the orders was dramatically neglected. In the other cases, production management was directly performed using specific developments, often using Excel® sheets, with similar lacks of functionalities.

*Main problems.* The main problem denoted by the large customers was that, in spite of their efforts for facilitating the work of their smallest subcontractors, the visibility of these subcontractors on the middle term work remained poor. This is, mainly due to an incomplete exploitation of the provided forecasts. Another cause was an inaccurate follow-up of the daily

activity, with the result of problems often lately identified. The consequence was usually brutal reactions which were destabilising their own subcontractors.

As a summary, an incomplete exploitation of the incoming business at tier 1 or 2 results in a lack of visibility which prevents from making the good decisions at the right moment in order to mitigate disturbances. Propagated upstream, this lack of visibility penalises the partners of the supply chain.

### ***3.3 Some lessons drawn from these examples***

When considering pragmatic problems occurring in a supply chain, the aeronautic industry is an interesting area since the final demand is rather stable (usually regularly increasing or decreasing). Therefore, most of the planning problems are linked to the communication between the partners of the supply chain, and not to external factors.

A centralised view on the supply chain does not seem to be relevant in this area, not because of the unavailability of planning tools (APS-Advanced Planning Systems could be used in that purpose) but mainly because of the necessary responsibility of each company concerning its own suppliers. In that context, each partner of the chain must keep its autonomy, also in its planning activities which condition its service to its customers.

It is seldom underlined in the literature that, as a chain, the efficiency of a supply chain depends on its weakest links, i.e. often the smallest companies, which usually have great technical know-how but less competence in production management.

It is now required to control and reduce the cycle times, in a context of increasing load. In that context, Ho *et al.*, (1995) describe methods considering the use of buffers such as safety stocks, safety lead times or safety capacity in order to manage uncertainty that may seem to be counter productive. The authors also stressed the importance of choosing a specific uncertainty management method consistent with the production environment, encouraging one to propose a “customized” approach in order to deal with uncertainty. Considering our interviews, we think that the supply chains, defined through the contracts between customers and sub-contractors, are able to manage the activity in a nominal situation. On the other hand, nothing is defined at the sub-contractors levels for i) early detection that something goes wrong; ii) finding adequate reactions, consistent with the time available for solving the problem. This statement is particularly true at the tactical decisional level, while methods for improving collaborative practices in the supply chain such as CPFR are mainly situated at the Stock-Keeping Unit level (Danese, 2006).

It is on the base of these statements that the framework described in next sections has been developed. Its ambition is not at all to define new concepts, but to formalise the minimum number of parameters allowing to model, then control, the coordination processes between partners in a supply chain.

## **4 Concepts for Enterprise Coordination within a Supply Chain**

### ***4.1 General Guidelines***

In consistence with the conclusions of the previous section, our framework focuses on the links between a production unit, its customers and its suppliers within a supply chain. It is more specifically concerned with the planning process of the production unit, which aims at

meeting the customer's demand at minimal cost while planning its own production and its procurement of raw material and components.

A dynamic planning process is suggested in a rolling horizon context, enabling to periodically update the customer's demand and to react to its fluctuations. The aim is to propose a quantitative planning model expressing the relationships between customers, suppliers and subcontractors, which can be used by each partner of the supply chain.

In a supply chain, the use of such model should allow to cope with some of the difficulties underlined in previous section. Especially, it should allow:

- to detect problems which have their origin in the production unit (backorders or insufficient capacity),
- to simulate the consequences of decision making in terms of reactivity and cost, taking into account the uncertainty of the demand. Degrees of freedom which have to be managed are for instance internal production vs. subcontracting, capacity adjustments, supply quantities, etc.,
- to evaluate the impacts of the complete, partial or non integration of the uncertain demand in the planning process,
- to provide assistance for customers/suppliers relationship by highlighting and evaluating possible improvement actions (reduction of cycle times and flexibility enhancement, etc.) (through “what-if” simulations).

Examples in section 7 show how the proposed framework helps to assess the impact of various parameters characterizing the performance of the supply chain.

#### ***4.2 Characteristics of the production entity***

Figure 1 summarises the data and material exchanges between the connected entities (suppliers, subcontractors and customers). This study is focused on the planning process of the "central" company (called "manufacturer" in figure 1) and on the impact of this process on other entities.

< insert Figure 1 around here >

The demand issued from customers is aggregated in order to generate the quantities to be delivered at each period  $t$  of a given planning horizon. This demand can be satisfied thanks to internal or subcontracted production. The unsatisfied demand at a given period generates backorders and associated penalty costs as long as the manufacturer does not provide the parts. Global lead times for internal or subcontracted production have to be taken into account in the planning process since they introduce a delay between the production dispatching period and the availability of the final products. Considering a global lead time embedding all the steps of the production process (producing, testing, delivering, etc.) is quite reasonable at a tactical level, where only a rough allocation of capacity is performed. This assumption has been confirmed by our interviews.

The global (aggregated) internal capacity of the manufacturer is known for each period of the planning horizon; it can be increased with over-costs by using extra-hours, additional shifts, etc. The use of extra-hours and of additional shifts show that the manufacturer can adopt and even cumulate two distinct reactions. On one hand, the use of extra-hours provides an

increase of capacity that can be precisely adjusted to the required level. Such reaction is mainly used to smooth small variations. On the other hand, the use of additional shifts implies major (long term) changes in the workforce. A global amount of capacity is then added even if a part of this amount is not required. The manufacturer can also selectively subcontract a part of its load; thus, the subcontractor is considered as a decisional lever for the production of final products. Moreover, the suppliers aim at delivering the components necessary for the production of end-items both for the consumption required by the internal and the subcontracted production. In that sense, the manufacturer is responsible for the availability of the components at the subcontractor's level. Several suppliers can be used for purchasing the same component. These suppliers differ by the selling price as well as their lead times.

Therefore, the planning manager has several degrees of freedom with different costs to react to fluctuations of the demand and to balance load and capacity: (i) smooth internal production and make inventories (ii) temporarily increase its internal capacity (iii) subcontract or (iv) allow backorders.

### ***4.3. Anticipation delay and reactivity***

In practice, decisions cannot be applied instantaneously, because organisational activities are often needed to prepare them. For example, changing the workforce organisation from 1-shift-work to 2-shift-work must be decided enough in advance in order to prepare the change (administrative procedures, organisation of new shifts, etc.). The *Anticipation Delay AD* of a decision is the time needed between the moment the decision is made and the moment this decision is effective. Thus, to be applicable at a given period  $t$ , a decision has to be made at least in period  $\tau$  with  $\tau \leq t - AD$ .

Anticipation delays depend on the nature of the decision: for example, changing to 2-shift-work may require an anticipation of 3 periods whereas the use of extra-hours may need only 1 anticipation period. Using a supplier may require an anticipation delay of  $n$  periods: this implies that it will be necessary to send the orders to this supplier at least  $n$  periods before the due date for receiving the components on time. In this case, we consider that the lead time of the supplier is embedded in its anticipation delay.

In the suggested approach, each kind of decision is characterized by its cost and its anticipation delay. This set of parameters makes the model richer and more consistent with reality. Hence, it is possible to model the fact that a supplier proposes to its customers several supply prices associated with different anticipation delays (the longer the anticipation delay, the cheaper the purchasing cost).

### ***4.4. Rolling horizon planning and frozen horizon***

In order to deal with the uncertainty on the data, the planning process is run periodically according to a rolling horizon of  $T$  periods. Let us call *PP* the re-Planning Period and  $PH^\tau$  the planning horizon considered at step  $\tau$ :  $PH^\tau = \{ \tau, \tau+1, \dots, \tau+T-1 \}$ . At each planning step, the external demand is updated and plans are regenerated to react to possible fluctuations. However, a decision relative to a period  $t$  cannot be modified at step  $\tau$  if its anticipation delay is not satisfied, i.e. if  $t \leq \tau + AD - 1$ . In order to be consistent, such decision has to be made earlier, i.e. in a previous planning step, and is necessarily "frozen" at step  $\tau$ . Thus, at each planning step and for each kind of decision, the planning horizon can be decomposed into two time-fences:

- a *frozen horizon*  $FH^t$ , corresponding to the relevant anticipation delay ( $FH^t = \{ \tau, \tau+1, \dots, \tau + AD - 1 \}$ ) within which decisions from previous planning steps are transferred without being modified,
- a *free horizon* within which decisions can be freely adapted to react to uncertainties and changes. The dynamic evolution of the planning process is described in figure 2 for a given kind of decision. In this example,  $T=6$ ,  $PP=2$  and the considered decision has a 3 periods anticipation delay. As we can see in figure 2, decisions concerning periods 4 and 5, made freely in the first planning step, are frozen and transferred without modifications in the second one. Decisions related to period 6 remain free in the second planning step.

< insert Figure 2 around here >

We emphasize here that the frozen horizon is adapted to each kind of decision instead of being a constant value in the re-planning process, as it is usually done at the tactical level in a MRP process.

With respect to the re-planning periodicity, anticipation delays and lead times are cumulative and give inertia to the production entity, reducing its ability to react and absorb disturbances so that variations in the demand. This implies that the customers' demand must be known early enough for being correctly anticipated ( $T$  must be as long as possible). On the other hand, reactivity is improved if anticipation delays, and thus frozen horizons, are as short as possible.

## 5 Planning model and dynamic planning process

At each step of the planning process, the manager must choose the best decisions among a large set of possibilities (internal production quantities, subcontracted production quantities, quantities ordered to suppliers, load smoothing, use of extra-hours or additional shifts, etc.) while integrating the decisions already made and now frozen, the cycle delays, costs, etc.

In this section, we propose a Linear Programming formulation of the planning problem (model  $M^t$ ) including the concepts outlined in the previous section. This model is then embedded in a dynamic framework enabling to simulate a complete planning process taking into account periodic updating of the customers' demand.

### 5.1 Model $M^t$ used at Each Planning Step

$M^t$  represents the planning problem at step  $\tau$ , over the planning horizon  $PH^t$ . In such a deterministic model, the demand is supposed to be known all over the planning horizon and is updated at each planning step.

The model is based on the following notations:

Sets and temporal parameters:

$\{p\}$  and  $\{c\}$ : sets of products  $p$  and components  $c$

$\{s\}$ : set of suppliers

$\{a\}$ : set of actions that may be activated to adjust the capacity of the manufacturer (i.e. 2 or 3-shifts-work).

$T$ : number of periods in the planning horizon

$PH^t$ : planning horizon at step  $\tau$ ;  $PH^t = \{ \tau, \tau+1, \dots, \tau+T-1 \}$

$FH_k^\tau$ : frozen horizon at step  $\tau$  associated to the decision  $k$  ( $k$  represents any kind of decision mentioned below);  $FH_k^\tau = \{ \tau, \tau+1, \dots, \tau+AD_{k-I} \}$

Static parameters (independent of the planning step  $\tau$ ):

$LP_p, LS_p$ : lead time for obtaining final products using respectively internal production or subcontracting

$C_t$ : internal capacity in period  $t$  (in hours)

$\kappa_a$ : overcapacity introduced by the use of action  $a$

$N_{p,t}$ : subcontractor capacity (expressed as a maximum quantity of products)

$\rho_p$ : unit processing time of final product  $p$ .

$\alpha_{p,c}$ : bill of material coefficients linking final product  $p$  and component  $c$ .

Dynamic parameters (updated at each planning step  $\tau$ ):

$\hat{D}_{p,t}^\tau$ : deterministic demand of final product  $p$  in period  $t$  resulting from all the customers.

Variables representing decisions made at step  $\tau$ :

$X_{p,t}^\tau$ : internal production of product  $p$  launched in period  $t$ .

$S_{p,t}^\tau$ : subcontracted production of product  $p$  launched in period  $t$ .

$E_t^\tau$ : extra-hours used in period  $t$ .

$B_{a,t}^\tau$ : (binary variable) = 1 if action  $a$  for increasing capacity is activated in period  $t$ , 0 otherwise.

$I_{p,t}^\tau, G_{p,t}^\tau$ : inventory and backorder levels at the end of period  $t$  for final products  $p$ .

$J_{c,t}^\tau$ : inventory level of component  $c$  at the end of period  $t$ .

$A_{s,c,t}^\tau$ : quantity of component  $c$  ordered to supplier  $s$  to be available in period  $t$

The Planning model is as follows:

$$\min \sum_{t=\tau}^{\tau+T-1} \left[ \sum_p i_p I_{p,t}^\tau + \sum_c j_c J_{c,t}^\tau + \sum_p g_p G_{p,t}^\tau + \sum_p x_p X_{p,t}^\tau + \sum_p s_p S_{p,t}^\tau + \sum_s \sum_c a_{s,c} A_{s,c,t}^\tau + \sum_a b_a B_{a,t}^\tau + e E_t^\tau \right] \quad (1)$$

Subject to:

$$I_{p,t}^\tau - G_{p,t}^\tau = I_{p,t-1}^\tau - G_{p,t-1}^\tau + X_{p,t-LP_p}^\tau + S_{p,t-LS_p}^\tau - \hat{D}_{p,t}^\tau \quad \forall p \quad \forall t \in PH^\tau \quad (2)$$

$$\sum_p \rho_p X_{p,t}^\tau \leq C_t + \sum_a (B_{a,t}^\tau \times \kappa_a) + E_t^\tau \quad \forall t \in PH^\tau \quad (3)$$

$$S_{p,t}^\tau \leq N_{p,t} \quad \forall p \quad \forall t \in PH^\tau \quad (4)$$

$$J_{c,t}^\tau = J_{c,t-1}^\tau - \sum_p \alpha_{p,c} (X_{p,t}^\tau + S_{p,t}^\tau) + \sum_s A_{s,c,t}^\tau \quad \forall c \quad \forall t \in PH^\tau \quad (5)$$

$$\sum_p [\alpha_{p,c} (X_{p,t}^\tau + S_{p,t}^\tau)] \leq J_{c,t-1}^\tau \quad \forall c \quad \forall t \in PH^\tau \quad (6)$$

$$E_t^\tau \leq E_{\max} \quad \forall t \in PH^\tau \quad (7)$$

$$X_{p,t}^\tau = X_{p,t}^{\tau-PP} \quad \forall p \quad \forall t \in FH_X^\tau \quad (8)$$

$$S_{p,t}^\tau = S_{p,t}^{\tau-PP} \quad \forall p \quad \forall t \in FH_S^\tau \quad (9)$$

$$A_{s,c,t}^{\tau} = A_{s,c,t}^{\tau-PP} \quad \forall s \quad \forall c \quad \forall t \in FH_{A_s}^{\tau} \quad (10)$$

$$B_{a,t}^{\tau} = B_{a,t}^{\tau-PP} \quad \forall a \quad \forall t \in FH_{B_a}^{\tau} \quad (11)$$

$$E_t^{\tau} = E_t^{\tau-PP} \quad \forall t \in FH_E^{\tau} \quad (12)$$

The objective function (1) aims at minimising the resulting cost of the whole plan.  $i_p, j_c, g_p, x_p, s_p, a_{s,c}, b_a, e$ , are the unitary costs associated to the relevant decision variables. Equation (2) links production quantities (subcontracted or not) and the inventories or backorders. Let us note that, because of the cycle time, production quantities launched in period  $t-LP$  or  $t-LS$  are available for use in period  $t$ . The production allowed in each period is limited by the production capacity (see Equation (3)) modelled as the sum of a standard capacity  $C_t$  available at each period, an overcapacity  $\kappa_a$  specific to actions defined in  $\{a\}$  and extra-hours  $E_t$  allocated per period. Constraint 4 limits the amount of products that can be subcontracted at each period  $t$ . The actions in  $\{a\}$  are cumulative and are activated by the binary variables  $B_{a,t}$ . This equation expresses that the products require the same resources. In equation (5), components inventories are calculated according to the production (subcontracted or not) and the bills of materials coefficients  $\alpha_{p,c}$ . Constraint (6) limits the final product assembly in period  $t$  by the stock of component available at the end of period  $t-1$ . Extra-hours  $E_t$  cannot exceed the maximum value  $E_{max}$  (7). Constraints 8 to 12 formalise the consistency of each kind of decisions between two consecutive planning steps taking into account their frozen horizons.

The plan  $P^{\tau}$  is the set of decisions obtained by solving  $M^{\tau}$ .

The model  $M^{\tau}$ , which takes into account a complex set of technical, temporal and financial constraints, can be used on its own by a manager as a decision support tool. It can also be integrated in a toolset enabling a whole planning process simulation and so, providing support for the supply chain parameterisation.

## 5.2 Principles for a Dynamic Use of the Model

A complete dynamic planning process can be simulated over a simulation horizon  $SH$  as depicted in figure 3. At each step  $\tau$ , planning decisions are made by solving model  $M^{\tau}$ . The dynamic parameters of the model are updated at each planning step. In order to illustrate the approach, we need to imitate the process of confirmation of the expected orders. In that purpose, a deterministic demand  $\hat{D}_{p,t}^{\tau}$  is generated over the relevant planning horizon according to a global profile predefined over the whole simulation horizon. Plans resulting from the previous steps are used to generate frozen decisions, work in progress, inventory levels, etc. needed at the current step  $\tau$ .

Such simulation tool is informative because it allows a comparison between various plans  $P^i$  obtained from different configurations of the supply chain and different demand profiles. These comparisons can be done for different values of  $T$  and  $PP$ , in relation with cycle times and anticipation delays, in order to assess the impact of the visibility the enterprise has on the customer demand. An example is given in section 7.2.

< insert Figure 3 around here >

At the end of a simulation, the decisions made are gathered in order to build the plan really implemented, denoted  $P^i$ . This construction process is depicted in figure 4 for a generic decision and is applied to each kind of decision in the global planning process simulation.

< insert Figure 4 around here >

In order to provide a reference for comparing a given plan to an optimal situation, a reference plan denoted  $P^{ref}$  has been built in a single iteration ( $PH^1 = SH$ ). In that case, the demand over the whole simulation horizon is supposed to be completely available at step 1, which would be the ideal case obviously not realistic.

The interest of this framework is increased in presence of uncertainty, since it enables the evaluation of different scenarios, depending on how the uncertainty is taken into account in the elaboration of the plans. The next section details how uncertainty can be integrated in the simulation framework.

## 6 Integrating uncertainty in the customer demand

Previous sections show that comprehensive decision anticipation is of prime importance, and that the planning process must be based on a long enough planning horizon. Practically, it is difficult for a company to have a good accuracy on the customer demand over a sufficient horizon. When the firm demands from the customers are not available enough in advance, the anticipation capabilities may be increased by incorporating forecasts. Thus, an uncertain demand must be taken into account in the planning process.

### 6.1 Modelling demand uncertainty and consolidation process

In our approach, in consistence with industrial practices (see section 3.2), the demand horizon at each planning step  $\tau$  is decomposed into two sub-horizons according to the nature of the demand: a **firm horizon** denoted  $RH^\tau$  and a **flexible horizon** denoted  $LH^\tau$ . The interest and practical use of such decomposition has been already argued by Rota (2002) in a comparable approach.

The demand over the firm horizon, denoted  $D_{p,t}^\tau$ , is supposed to be perfectly known and thus, will not change through time. On the other hand, the demand is uncertain and not precisely known over the flexible horizon. We assume here that this uncertainty is modelled through a range of values  $[\underline{D}_{p,t}^\tau, \overline{D}_{p,t}^\tau]$  for each product and period, which is the less constraining hypothesis which can be done. These lower and upper bounds describe the “flexible demand” transmitted at time  $\tau$  by the customer to the manufacturer, and delimit possible values for the real, firm, demand that will be specified later on by the customer.

At step  $\tau$ , the planning must be performed according to the available data, i.e. firm or flexible demand according to the period:  $\{D_{p,t}^\tau, \forall t \in RH^\tau, [\underline{D}_{p,t}^\tau, \overline{D}_{p,t}^\tau] \forall t \in LH^\tau\}$ .

Between two planning steps, the knowledge on the future demand becomes more accurate: some flexible orders are consolidated and become firm; new flexible orders are introduced at the end of the current planning horizon. We assume here that firm demand resulting from the consolidation process is necessarily included in the range specified earlier, but this hypothesis is not mandatory since it is only used for the simulation of the “real” demand: in real use, this real demand will of course be known, and not simulated.

The dynamic evolution of the demand between two successive planning steps is formalised through the following relations:

$$D_{p,t}^{\tau} = D_{p,t}^{\tau-PP} \quad \forall p \quad \forall t \in \{RH^{\tau-PP} \cap RH^{\tau}\} \quad (13)$$

$$D_{p,t}^{\tau} \in \left[ \underline{D}_{p,t}^{\tau-PP}, \overline{D}_{p,t}^{\tau-PP} \right] \quad \forall p \quad \forall t \in \{FH^{\tau-PP} \cap RH^{\tau}\} \quad (14)$$

$$\left[ \underline{D}_{p,t}^{\tau}, \overline{D}_{p,t}^{\tau} \right] = \left[ \underline{D}_{p,t}^{\tau-PP}, \overline{D}_{p,t}^{\tau-PP} \right] \quad \forall p \quad \forall t \in \{FH^{\tau-PP} \cap FH^{\tau}\} \quad (15)$$

Equation (13) shows that firm demands are not modified between successive planning steps. New firm demands resulting from the simulated consolidation process remain consistent with their previous flexible values (14) (in a real context, the consolidation is of course provided by the customer). Flexible demands do not change between two planning steps (15).

This approach is consistent with the case studies summarised in section 3.2, in which this principle was a common point between the interviewed companies: the decomposition in firm and flexible orders corresponds to a shared risk between the manufacturer and its customers. The customer often engages his responsibility to maintain firmly ordered quantities and to respect the defined bounds when the orders become firm. As far as the flexible demand correctly delimits the future real demand, the manufacturer has to satisfy firm orders, whatever their values.

### 6.3 Planning strategies

At each step, the planner has at its disposal *firm* and *flexible* (thus uncertain) demands. Its task is difficult: indeed, given the need of anticipation and the delays discussed in previous sections, some planning decisions are based on flexible orders and must nevertheless be frozen. Thus, it will be impossible to adjust them when real firm demand will be available. In such uncertain context, the decision maker will choose which part of the flexible demand he will integrate in his planning process. In order to imitate this reasoning, we propose to define typical “planning strategies”. The purpose of a planning strategy is so to transform flexible (uncertain) demands into deterministic values, thus allowing to perform a planning. In our case, the planning will again be defined using the model developed in section 5-1 as a decision support. Hence, at each planning step, the model  $M^{\tau}$  is solved with:

$$\widehat{D}_{p,t}^{\tau} = D_{p,t}^{\tau} \quad \forall p \quad \forall t \in RH^{\tau} \quad (16)$$

$$\widehat{D}_{p,t}^{\tau} = f(\underline{D}_{p,t}^{\tau}, \overline{D}_{p,t}^{\tau}) \quad \forall p \quad \forall t \in LH^{\tau} \quad (17)$$

where  $f$  represents the planning strategy.

Without loss of generality, since any choice is acceptable, three elementary strategies are considered here as illustrations:

- an “optimistic” strategy : the planning is done considering an optimistic interpretation of the flexible demand, i.e. its upper bound :

$$\widehat{D}_{p,t}^{\tau} = \overline{D}_{p,t}^{\tau} \quad \forall p \quad \forall t \in LH^{\tau} \quad (18)$$

- a “pessimistic” strategy : the planning is done according to a pessimistic interpretation of the flexible demand, i.e. its lower bound :

$$\widehat{D}_{p,t}^{\tau} = \underline{D}_{p,t}^{\tau} \quad \forall p \quad \forall t \in LH^{\tau} \quad (19)$$

- an “average” strategy : the planning is done according to the average of the bounds characterizing the flexible demand :

$$\widehat{D}_{p,t}^{\tau} = \frac{D_{p,t}^{\tau} + \overline{D}_{p,t}^{\tau}}{2} \quad \forall p \quad \forall t \in LH^{\tau} \quad (20)$$

Any other strategy can of course be considered, based either on quantitative information (distribution laws providing the most probable demand, linear regression exploiting past demands, etc.) or on qualitative ones (market tendencies, customers' habits, confidence in the customer, results of the previous planning steps etc.).

#### **6-4 Evaluation of strategies**

The simulation framework presented in section 5-2 can be used to simulate a complete planning process based on a specified planning strategy. The impact of the planning strategy can then be evaluated in terms of risks incurred (overstocks, backlogs, etc) and costs. To carry out a simulation, it is necessary to choose the planning strategy and the "context" in which this strategy is assessed, this "context" being defined by the consolidation process allowing to turn "flexible" orders into firm orders (cf. Equation 14). Different contexts can be considered, among which:

- the "lower bound" context : firm orders correspond to the lower bounds of relevant flexible orders
- the "upper bound" context : firm orders correspond to the upper bounds of relevant flexible orders
- the "random" context : firm orders are randomly generated within the range of the flexible orders.

These contexts simulate the profile of the real demand that will be considered in a simulation experiment. When an optimistic (resp. pessimistic) planning strategy is assessed in a lower bound (resp. upper bound) context, a worst case evaluation is obtained, highlighting costs and risks incurred when the planning strategy proves to be inconsistent with the real demand. Similarly, a best case evaluation can be derived from the simulation framework.

The simulation framework provides a useful decision support to the manager who has to choose a planning strategy to face an uncertain demand.

### **7 Use of the framework for Problem Solving**

In this section, some possible applications of this simulation framework are developed on an example deliberately simplified for clarity reasons. After a description of this example, two main problems are addressed as illustrations. The first one concerns the evaluation of the need for visibility of the manufacturer. The second one concerns the choice of a flexible demand integration strategy through, simulation, evaluation and comparison of the possible strategies.

#### **7.1 Description of the Example**

The example is based on the structure depicted in figure 1. It involves a manufacturer  $M$  in relation with a subcontractor  $SUB$  and two suppliers  $S1$  and  $S2$ . The manufacturer  $M$  assembles one final-product  $F$  composed of two items  $C1$  and  $C2$  both available from each supplier.  $S2$  has higher prices than  $S1$  but requires less anticipation. The capacity adjustments of  $M$  consist in using extra-hours or subcontracting. Table 1 and 2 list delays and costs associated to each kind of decisions.

< insert Table 1 around here >

< insert Table 2 around here >

According to these parameters, several simulations with a constant Planning Periodicity  $PP$  of 2 periods have been conducted in order to show how the simulation tool can be used for decision support. Different aspects are here more specifically analysed: (1) the impact of the visibility on the demand in a deterministic context and (2) the outcomes of three planning strategies regarding different demand profiles.

### ***7.2 Evaluation of the need for visibility***

This first example deals with a deterministic context. Considering the parameters characterizing the manufacturer and its relations with the others entities (production and subcontracting lead times, anticipation delays, etc.), the purpose is to study how the performance evaluated with global costs is impacted by the actual visibility on the demand, i.e. by the length of the planning horizon  $T$ . Flexible demands are not integrated in this experiment, thus, the planning can be considered as “myopic”. Figure 5 shows, over the whole simulation horizon ( $SH = 26$  periods), the demand that the manufacturer will have to satisfy in a deterministic context, as well as the available capacities (internal, subcontracted or extra-hours capacities). According to the periodic planning process, the demand will be progressively made available to the planning model.

< insert Figure 5 around here >

< insert Figure 6 around here >

Figure 6 shows the costs of the implemented plans resulting from simulations according to the length of the planning horizon  $PH^t$ . The results given in figure 6 confirm the good-sense assumption that an increased visibility leads to a global cost diminution. Indeed, the problem is here to have a visibility greater than the time needed for reacting to disturbances and smooth the production load. Here, a rolling horizon planning process with a planning horizon of 14 periods yields the same global cost than the reference plan since this planning horizon is longer than the maximum cumulative lead times and anticipation delays (4 periods). This is due to the peak of demand that must be known sufficiently in advance to be optimally smoothed according to capacity constraints.

This kind of simulation and reasoning gives an objective justification of the empirical interest to know the demand in advance. The manufacturer can argue towards its customer for the need of an increased visibility and evaluate the expected benefit compared to its current situation. Of course, the real problem is the availability of accurate data at the given horizon. The interest is here to show the benefit which can be obtained from this knowledge, and so the cost which is acceptable for getting this information (for instance by implementing a CRM (Customer Relationship Management) software in order to increase the horizon of the forecasts).

### ***7.3 Forecasts Integration and Strategy Selection***

As described in section 6, flexible orders can be transmitted from customers to the manufacturer in the aim of improving its anticipation capabilities. In this case, the latter has to check that the integration of flexible orders is meaningful and he must choose the best planning strategy.

The simulation framework can be used in order to run “what-if” simulations and to compare the outcomes of the planning strategies in different contexts. Three different strategies (Optimistic, Average and Pessimistic) are evaluated here for illustration purpose with three different evaluation contexts (Upper Bound, Lower Bound and Average). The considered flexible demands are those depicted in figure 7. In that uncertain context, the bounds characterizing flexible orders have been chosen here as +/- 20% of the average demand profile given in figure 7.

< insert Figure 7 around here >

Simulations are done considering at each step a firm and a flexible horizon of respectively 8 and 4 periods. Thus, the planning horizon covers 12 periods at each step.

The comparison of the different strategies in the different evaluation contexts is not easy, since the real demand depends on the context. For simplification purpose, we consider the global gain induced in each case by the plan, which is more meaningful than the cost of the plan. The gain is calculated as the selling price of a final product multiplied by the global quantity of sold products minus the global cost of the plan. Table 3 shows the gains obtained by applying each planning strategies with each possible context. To complete the analysis, the "ideal" gain obtained using the whole reference plan is given for each context.

< insert Table 3 around here >

Different points must be underlined in this example. Due to the lack of visibility and thus the reduced anticipation, the reference gain for each context is not always obtained even by the best strategy (except for Lower Bound context for which the Pessimistic strategy reaches the gain obtained with the reference plan). Moreover, there is no strategy providing the best result whatever the context. In order to choose between these strategies, some decision criteria can be used by the manager to support its decision making. One of the most common is the Wald criterion (Wald, 1950) (also known as the *Maximin*). For each strategy, we consider the minimum outcome obtained among the different evaluation contexts i.e. 143 604 for the optimistic strategy, 144 415 and 136 556 for the average and pessimistic strategy respectively. The *Maximin* criterion suggests to choose the strategy which generates the highest of the minimum outcomes. In this example, it is thus the average strategy. Of course, different criteria can be developed and taken into account; the matter here being to highlight how the proposed approach can be used as a decision support.

## **8 Conclusion and Perspectives**

In this article, we propose a planning model which main features have been driven by real practices outlined during interviews led in several companies, mainly from the aeronautical industry. Especially, the model copes with the reactivity capabilities of the planned system and of its environment (suppliers, subcontractors and customers) as well as the costs of these reactivity means. Through the definition of planning strategies, the model also allows to imitate the behaviour of the manager facing uncertain or flexible demand. Moreover, the model is embedded in a framework simulating a rolling horizon planning process based on a dynamic demand acquisition.

Hence, through a comprehensive understanding of the concepts undertaken by the management of the uncertainty in the customer demand, guidelines for defining a tactical

response assessing risks of overstocks, obsolescence or backorders are given. In this approach, the emphasis has been put on the possibility to support a collaborative improvement process regarding the visibility on the customer demand. In that way, the decrease of costs obtained thanks to a better visibility on the demand provides a performance indicator that can help a manager to argue for a better implication of its clients in the definition of their demand.

The framework developed in this article is thus offering the ability of “what-if” assessments. This simulation framework is built as an adaptive tool enabling the manager to model, integrate and evaluate several strategies and parameters according to its requirements in terms of areas of improvements.

Finally, since the model embedded in the simulation is at a rather abstract level, other studies focusing on variations of specific parameters that have not been considered in this article are possible. This approach could be applied to each parameter considered in the model (costs, delays etc.). Each modification in the value of the considered parameter will have an impact over the performance (costs, levels of backorders etc.). The comparison of such impacts will help the manufacturer to determine which parameter requires to be firstly modified. As a perspective, the use of possibility theory for modelling the flexible demand on the base of expertise seems to be a promising approach for a more explicit consideration of uncertainty.

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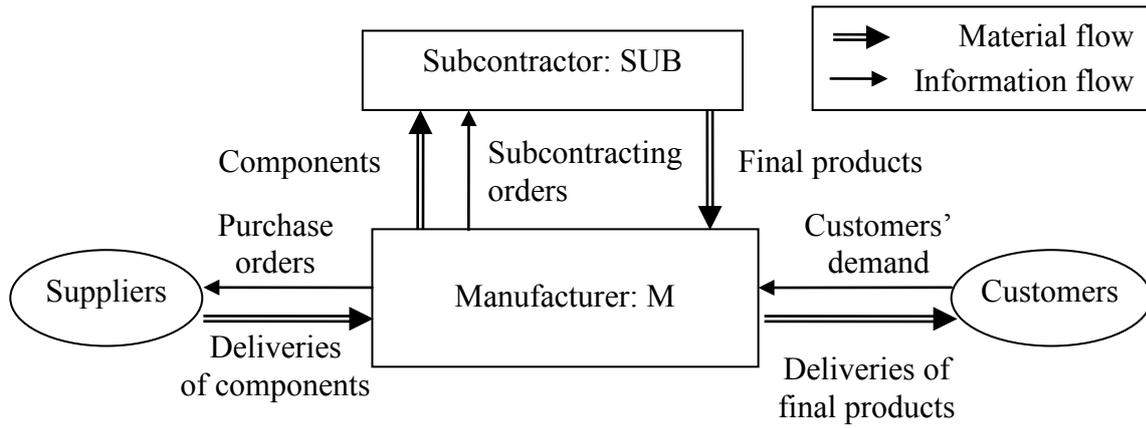


Figure 1. Exchanges of an entity of the supply chain with its environment

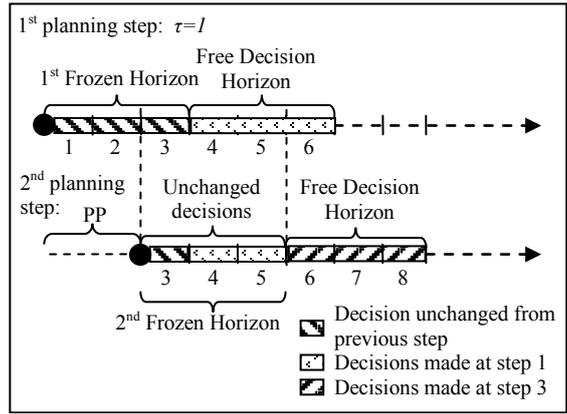


Figure 2. Planning process with  $T=6$ ,  $PP=2$ ,  $AD=3$

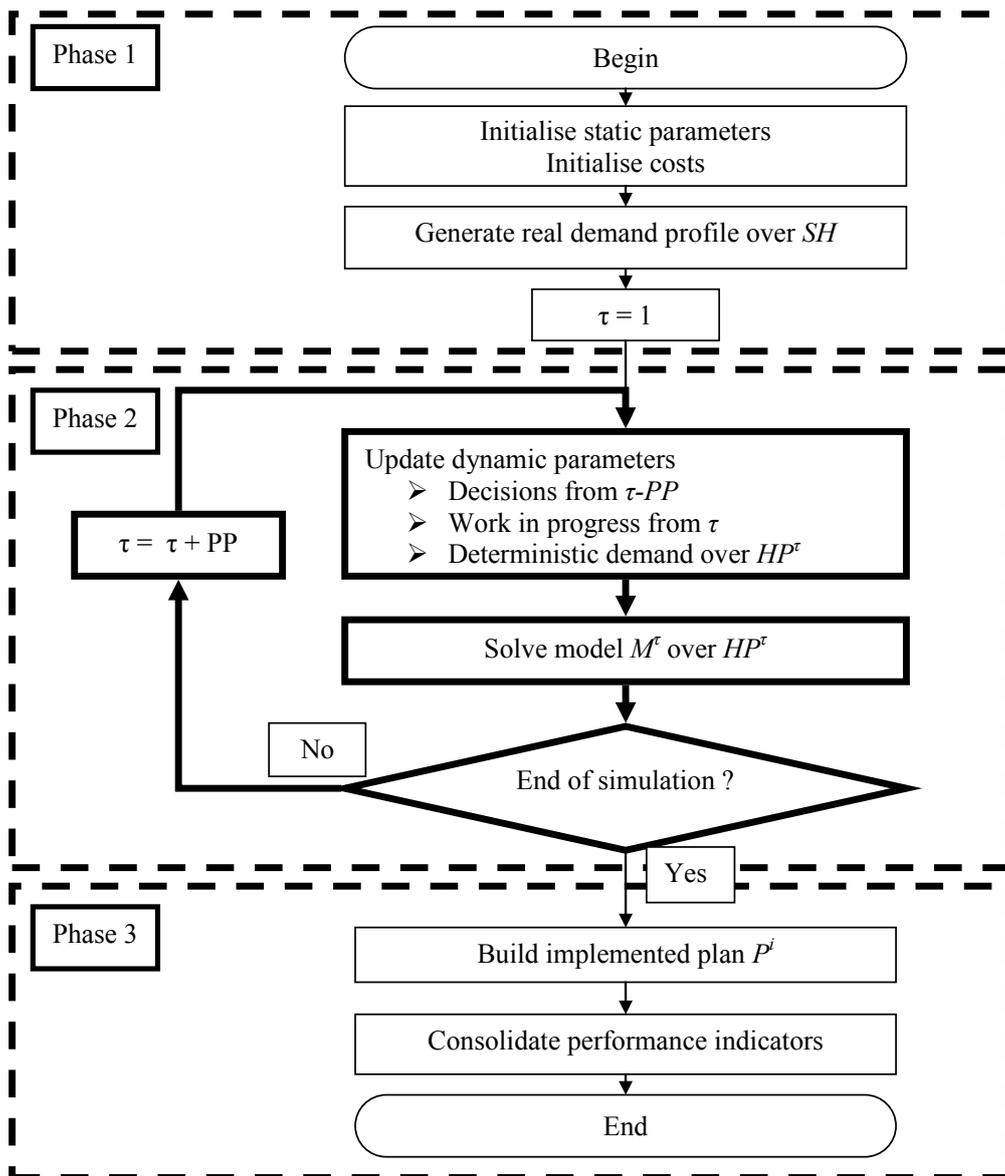
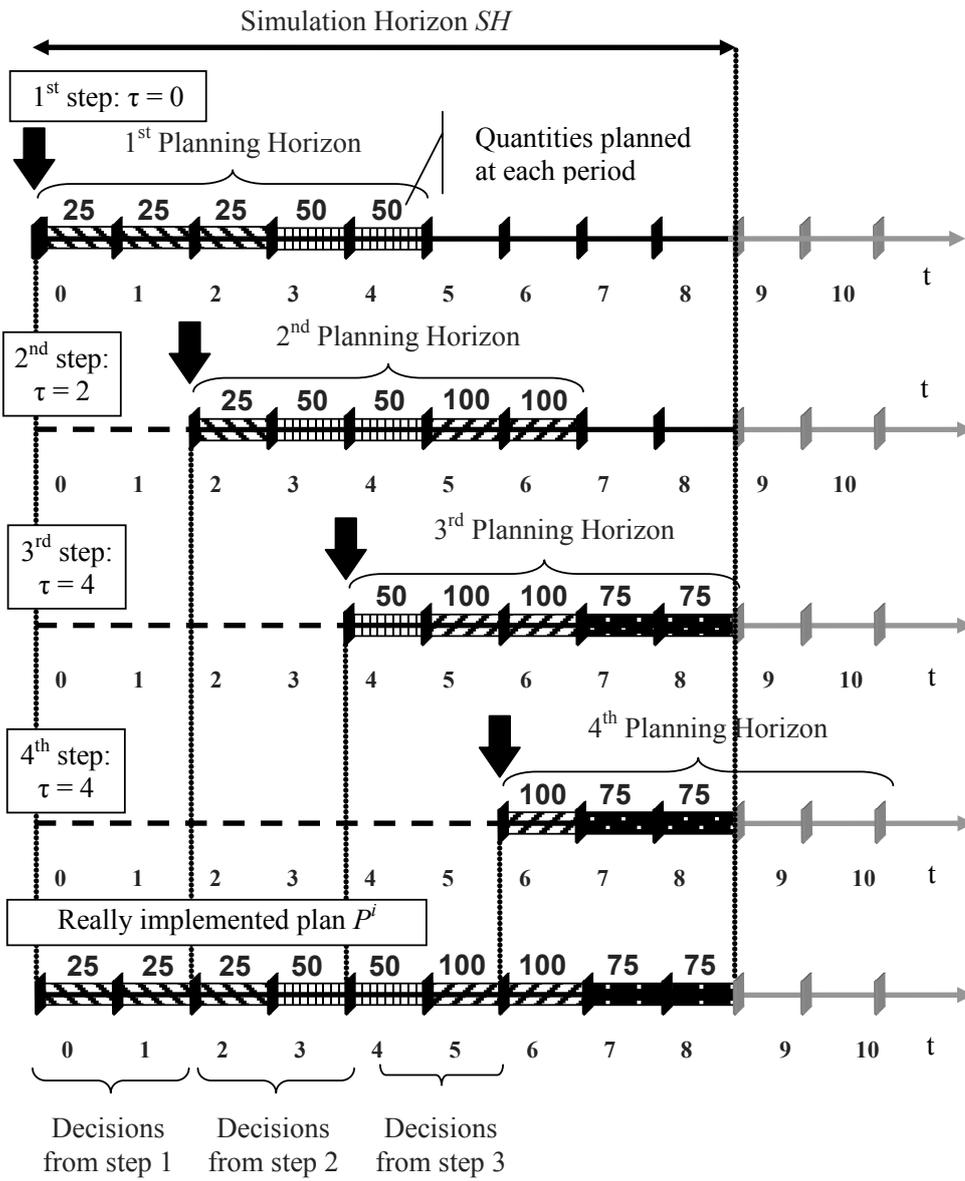


Figure 3. Simulation framework



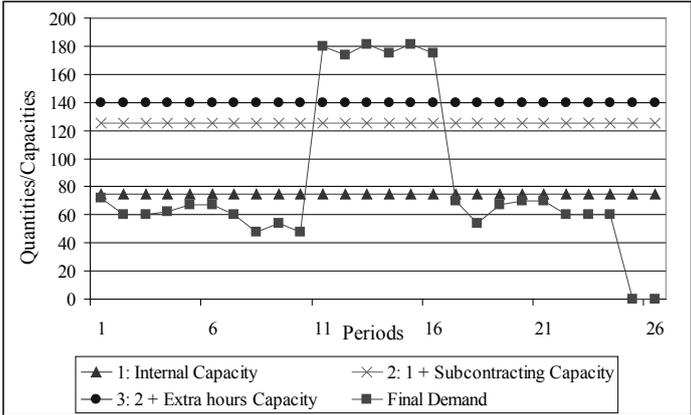


Figure 5. Demand profile compared to cumulated capacities

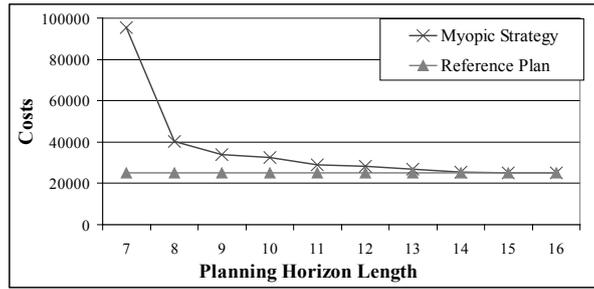


Figure 6. Impact of increasing visibility on costs of the implemented plans

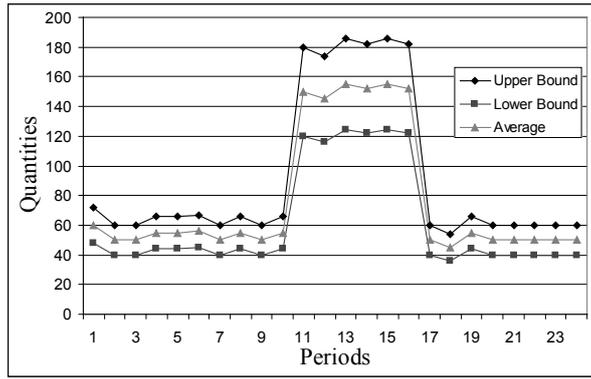


Figure 7. Firm demand and flexible bounds profiles

Table 1. Delays and costs for the decisions concerning the production.

Decision	Anticipation Delay	Lead time	Unit cost
Internal Production	0	0	10
Subcontracting	2	2	15
Extra-hours	1	N/A	35
Purchases with S1	3	N/A	cf. Table 2
Purchases with S2	1	N/A	cf. Table 2

Table 2. Purchasing, storage and backlog costs

Item	Purchases with S1		Purchases with S2		Storage		Backlogs	
	C1	C2	C1	C2	C1	C2	F	F
Unit cost	0,5	0,1	2	1	0,05	0,01	4	100

Table 3. Outcomes of different strategies against specific demand profiles

	Lower Bound	Average	Upper Bound
Reference plan	144 672	177 683	207 915
Optimistic strategy	143 604	177 207	195 210
Average strategy	144 415	175 237	174 017
Pessimistic strategy	144 672	169 855	136 566